National Aeronautics and
Space Administration

Airborne Double Pulsed 2-micron IPDA Lidar for Atmospheric CO_2 Measurement

Jirong Yu, Mulugeta Petros, Tamer Refaat, Upendra Singh

NASA Langley Research Center

OSA Optics and Photonics for Energy & the Environment (E2)
November 2-5, 2015

Acknowledgement: NASA Earth Science Technology Office (ESTO)

www.nasa.gov
http://engineering.larc.nasa.gov/

Outline

- **Introduction**
- **2-micron Double Pulsed IPDA Lidar**
  - Methodology
  - Spectroscopy and IPDA Simulation
  - Lidar System Development
  - Airborne Demonstration
- **Summary and Conclusions**

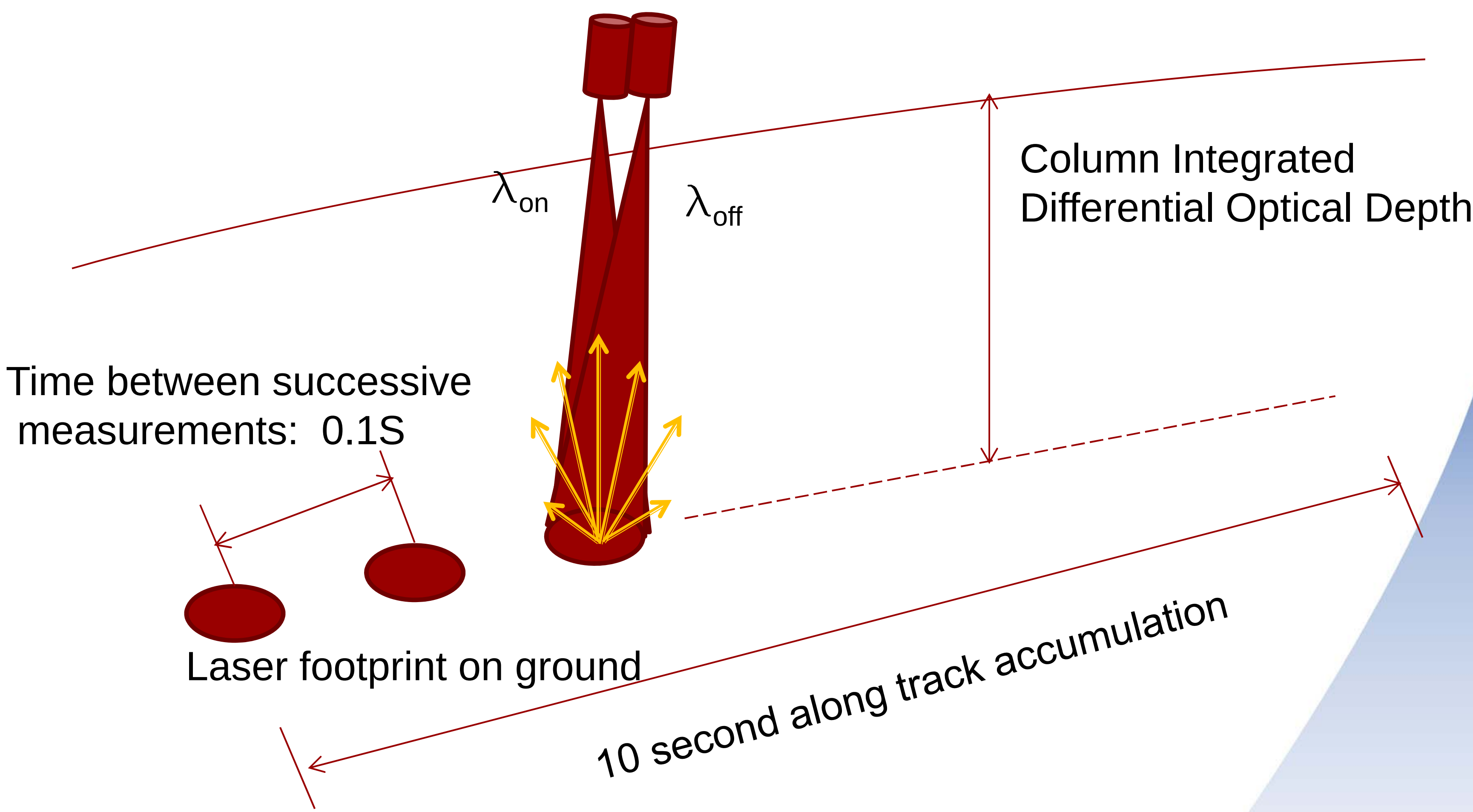
Introduction

- The study of global warming needs precisely and accurately measuring greenhouse gases concentrations in the atmosphere. CO_2 and H_2O are important greenhouse gases that significantly contribute to the carbon cycle and global radiation budget on Earth
- NRC Decadal Survey recommends a mission for Active Sensing of Carbon Dioxide (CO_2) over Nights, Days and Seasons (ASCENDS)
- 2 micron laser is a viable IPDA transmitter to measure CO_2 and H_2O column density from space
- The objective is to demonstrate a first airborne direct detection 2 micron IPDA lidar for CO_2 measurements.

2μm Pulsed Lidar Approach

- Unambiguously defines the optical path of the detected signal; eliminate contamination from aerosols and clouds to yield high accuracy measurements
- Auxiliary altimetry lidar may not needed
- The weighting function in the 2-μm region is most favorable for making CO_2 measurements near the surface and PBL, where the sources and sinks of CO_2 are located
- Straightforward data analysis
- The pulse approach can potentially determine CO_2 concentrations as a function of distance, a valuable data product that is not easily available

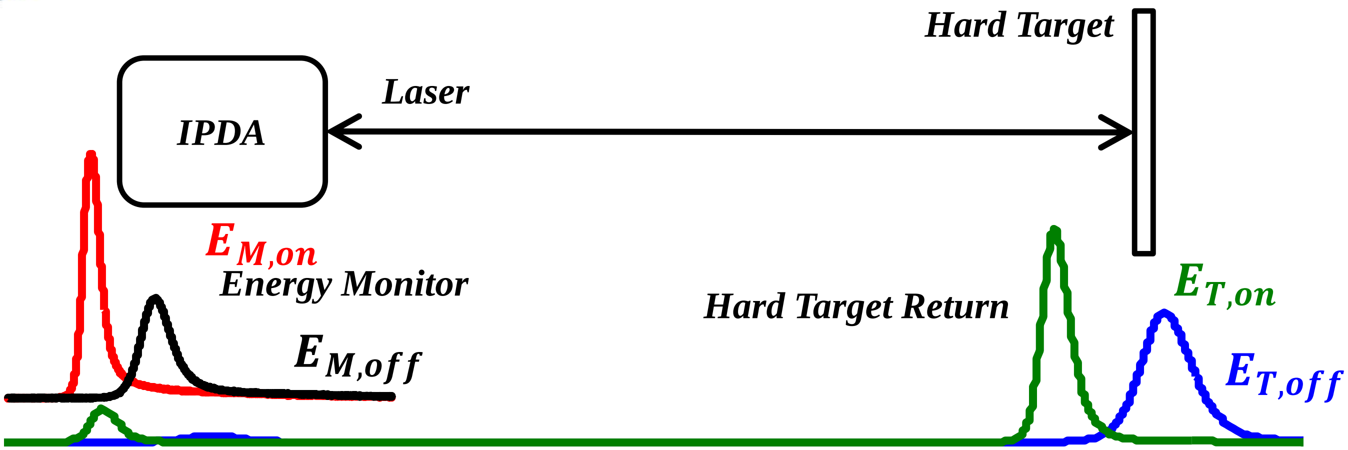
Principle of IPDA Measurement Using Surface Targets



Transmit and receive near nadir-pointing laser beams with on and off-line wavelength channels

- Ground surface reflection (land and sea)
- Measure difference in integrated path absorption at these two wavelengths

Methodology



- IPDA lidar relies on the Hard Target Lidar Equation

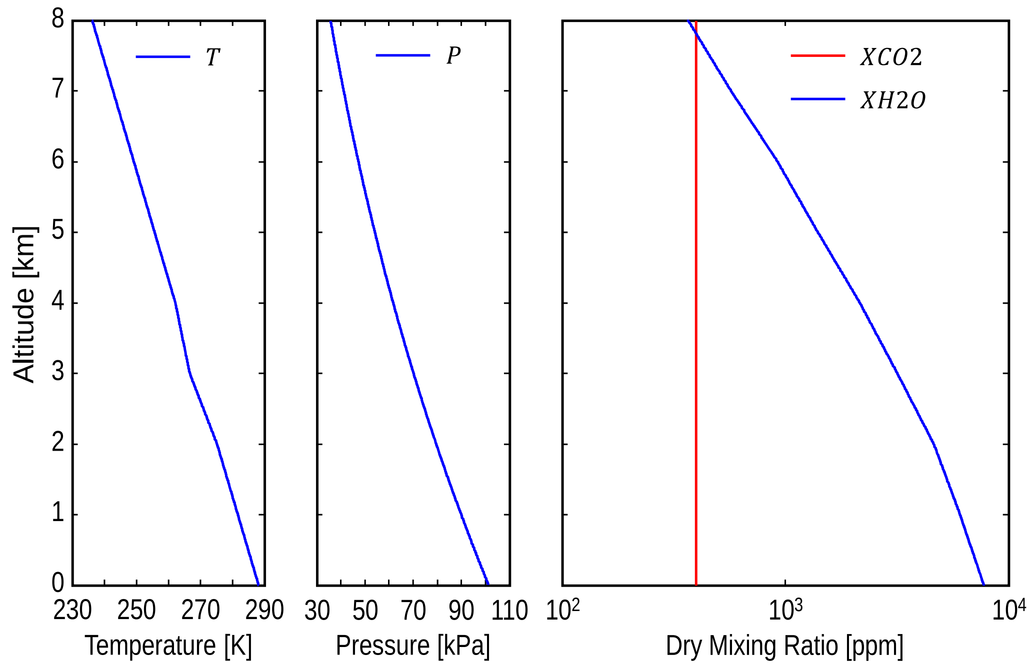
$$E_T = \eta_r \cdot \varphi_r \cdot \frac{A_t}{\Delta R^2} \cdot E_M \cdot \frac{\rho}{\pi} \cdot exp[-OD(\lambda, R_G)]$$

- Double-pulse tuning defines CO_2 differential optical depth, the main IPDA product

$$DAOD_{cd} = \int_0^R 2 \cdot \Delta\sigma_{cd} \cdot N_{cd} \cdot dr \approx ln\left(\frac{E_{T,off} \cdot E_{M,on}}{E_{M,off} \cdot E_{T,on}}\right)$$

- Other IPDA products include ranging and surface reflectivity.

Modeling: XCO2 Extraction



US Standard Atmospheric Model.

- Provided availability of meteorological data, differential optical depth can be converted into dry mixing ration (XCO2)

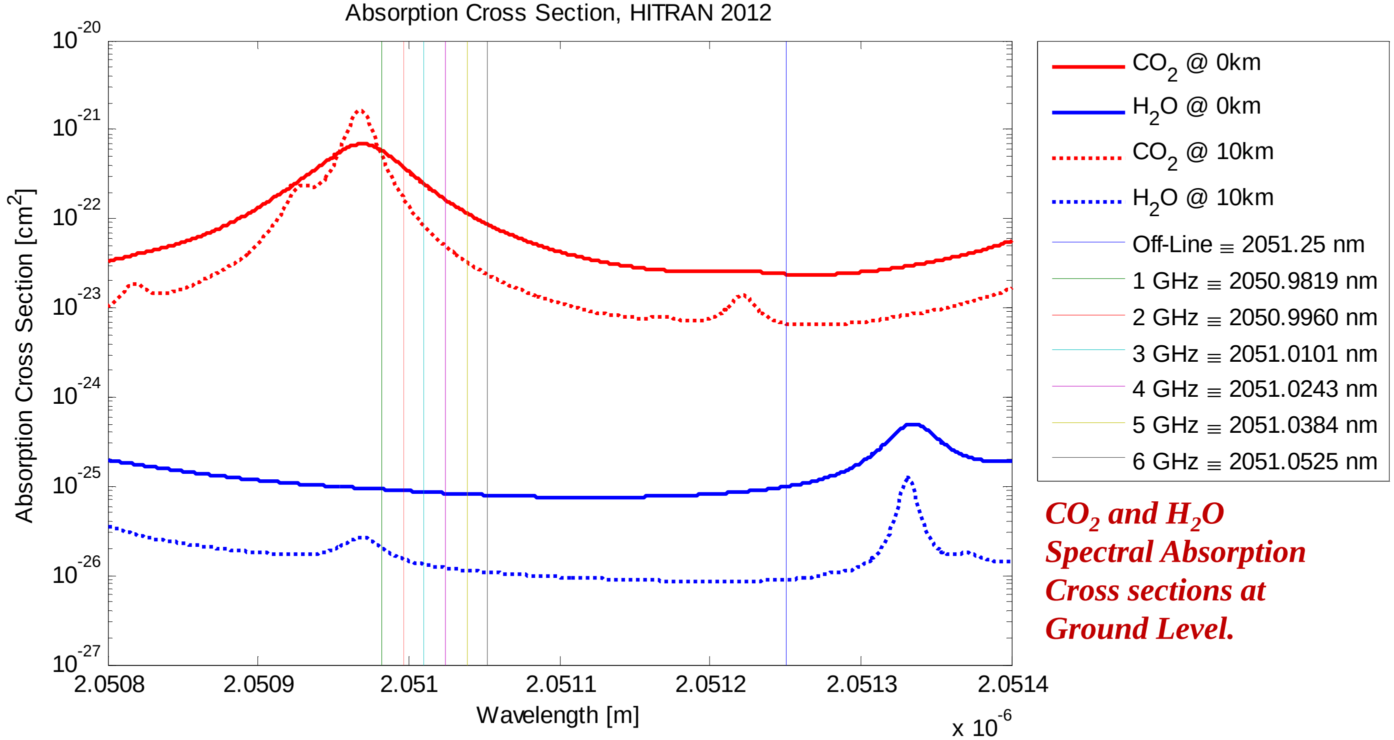
$$N_{dry} = N_{air} - N_{wv}$$

$$N_{wv} = fn(RH)$$

$$N_{air} = \frac{P}{k \cdot T}$$

$$XCO2 = \frac{DAOD_{cd}}{\int_0^R 2 \cdot \Delta\sigma_{cd} \cdot N_{dry} \cdot dr} = \frac{N_{cd}}{N_{dry}}$$

Modeling: Spectroscopy

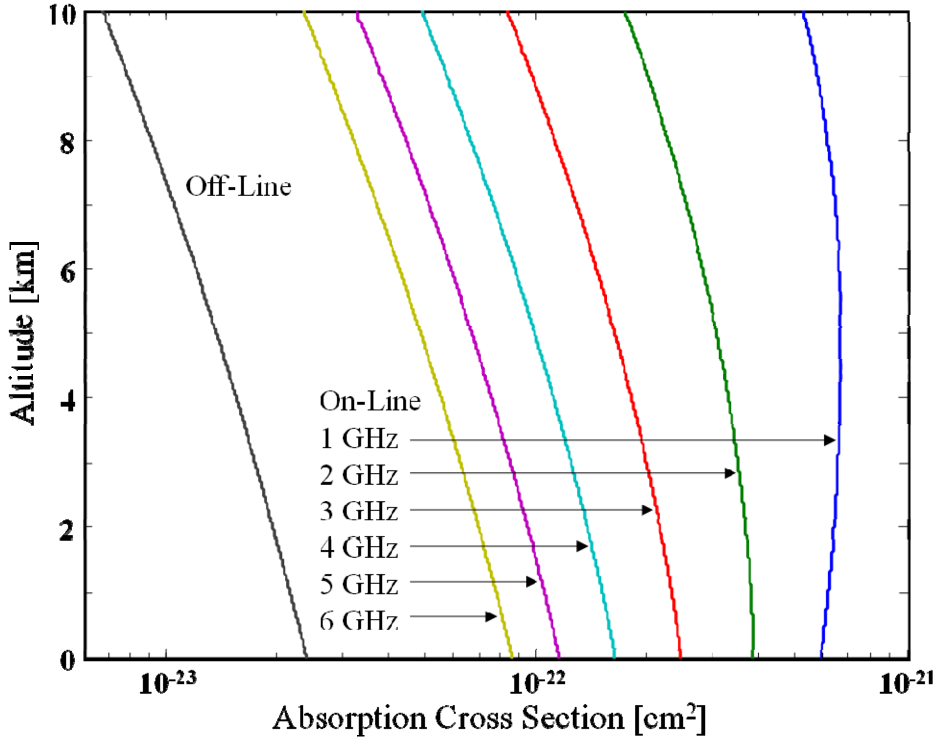


CO_2 and H_2O Spectral Absorption Cross sections at Ground Level.

$$\Delta\sigma_{cd} = fn(\lambda, P, T)$$

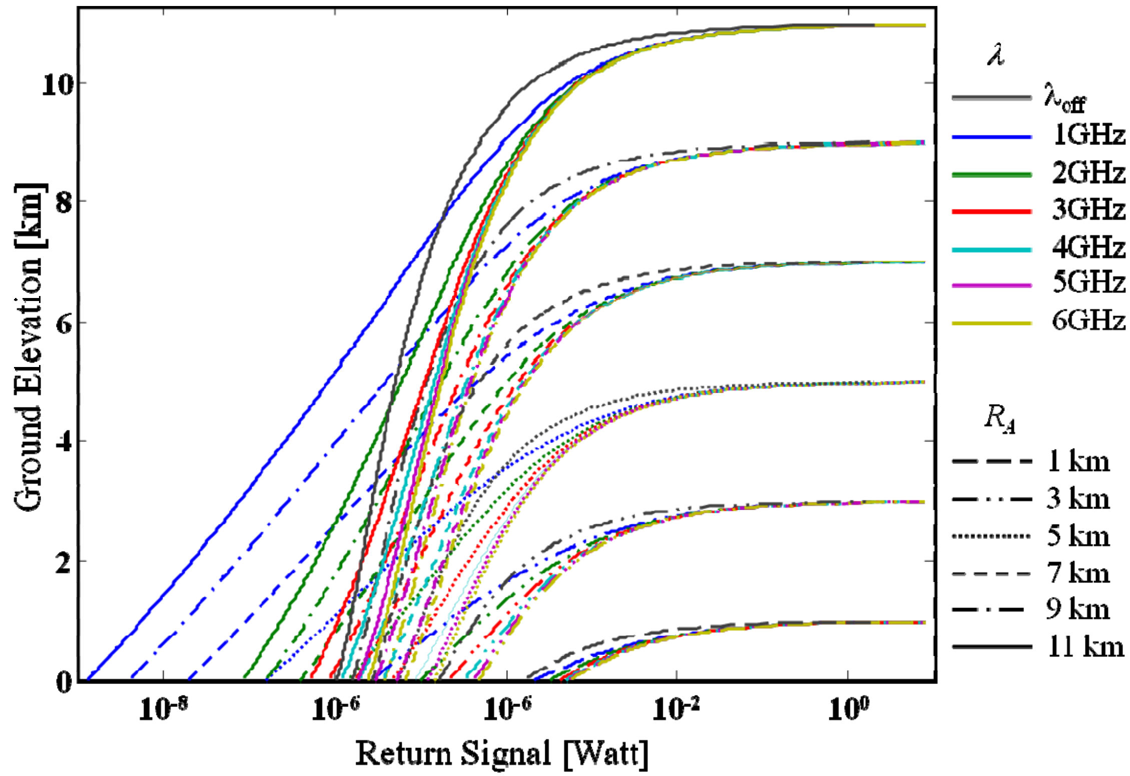
- Calculated using HITRAN 2012 database targeting CO_2 R30 line
- Voigt line profile was assumed
- Calculation includes 5550 CO_2 neighboring lines from 2044.22 nm to 2059.57 nm
- Calculation includes 1816 H_2O neighboring lines from 2022.21 nm to 2080.36 nm
- US Standard Atmospheric model was assumed

Modeling: *CO_2 Vertical Absorption Profiles*



Absorption profiles are used for evaluating the CO2 weighting-functions, applied to convert the IPDA optical depth measurement into weighted average column dry-air volume-mixing ratio for comparison to in-situ sensors

Modeling: *IPDA Lidar Return Power*



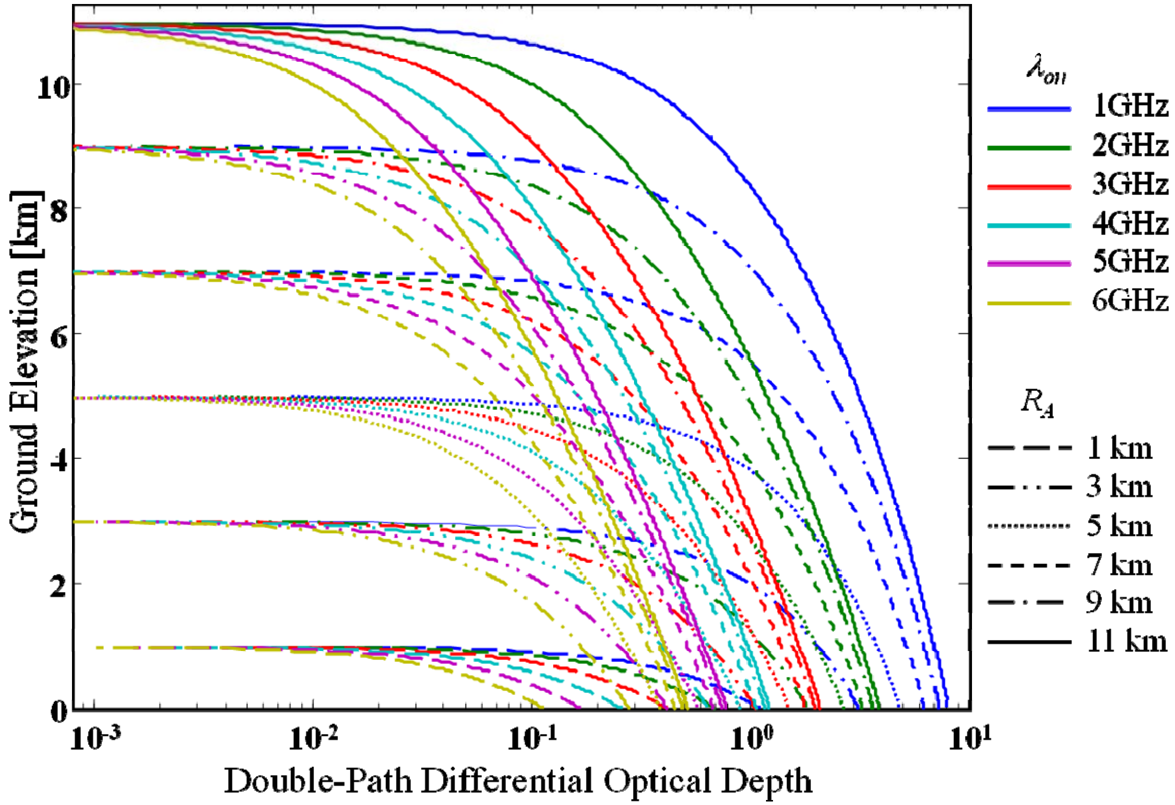
Calculated for nadir operation from ocean surface at different operating conditions.
Calculation based on the hard target lidar equation

$$P = \eta_r \cdot \varphi_r \cdot \frac{A}{(R_A - R_G)^2} \cdot \frac{E}{t} \cdot \frac{\rho}{\pi} \cdot T$$

For fixed on-line, transmission is based on the molecular and aerosol optical depths

$$T = \exp\left(-OD_{cd} - OD_{wv} - OD_A\right)$$

Modeling: *Double-Path Differential Optical Depth*



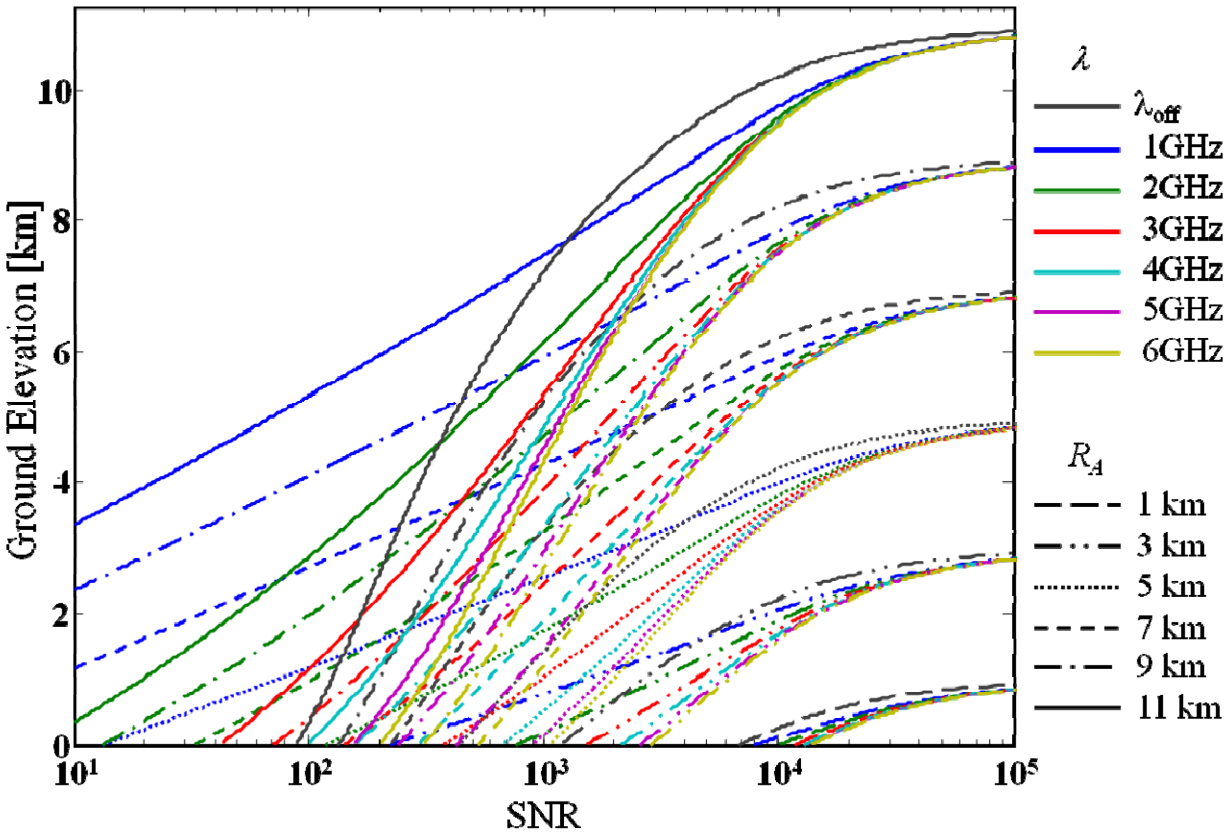
CO_2 double-path optical depth is modeled according to

$$OD_{cd} = 2\int_{R_G}^{R_A} \sigma_{cd} \cdot N_{cd} \cdot dr$$

CO_2 differential optical depth, at different operating conditions

$$dOD_{cd} = OD_{cd}\left(\lambda_{on}\right) - OD_{cd}\left(\lambda_{off}\right)$$

Modeling: *IPDA Lidar Signal-to-Noise Ratio*



SNR calculated as the ratio of the return power to the total noise power.
Total noise power obtained by combining instrument fixed noise and signal dependent shot noise.
Fixed noises include electronic noises and background radiation.
Dominant electronic noises sources, such as detector dark current and TIA feedback Johnson noise, input current and voltage noises and coupling noise, were considered

IPDA Lidar Specification

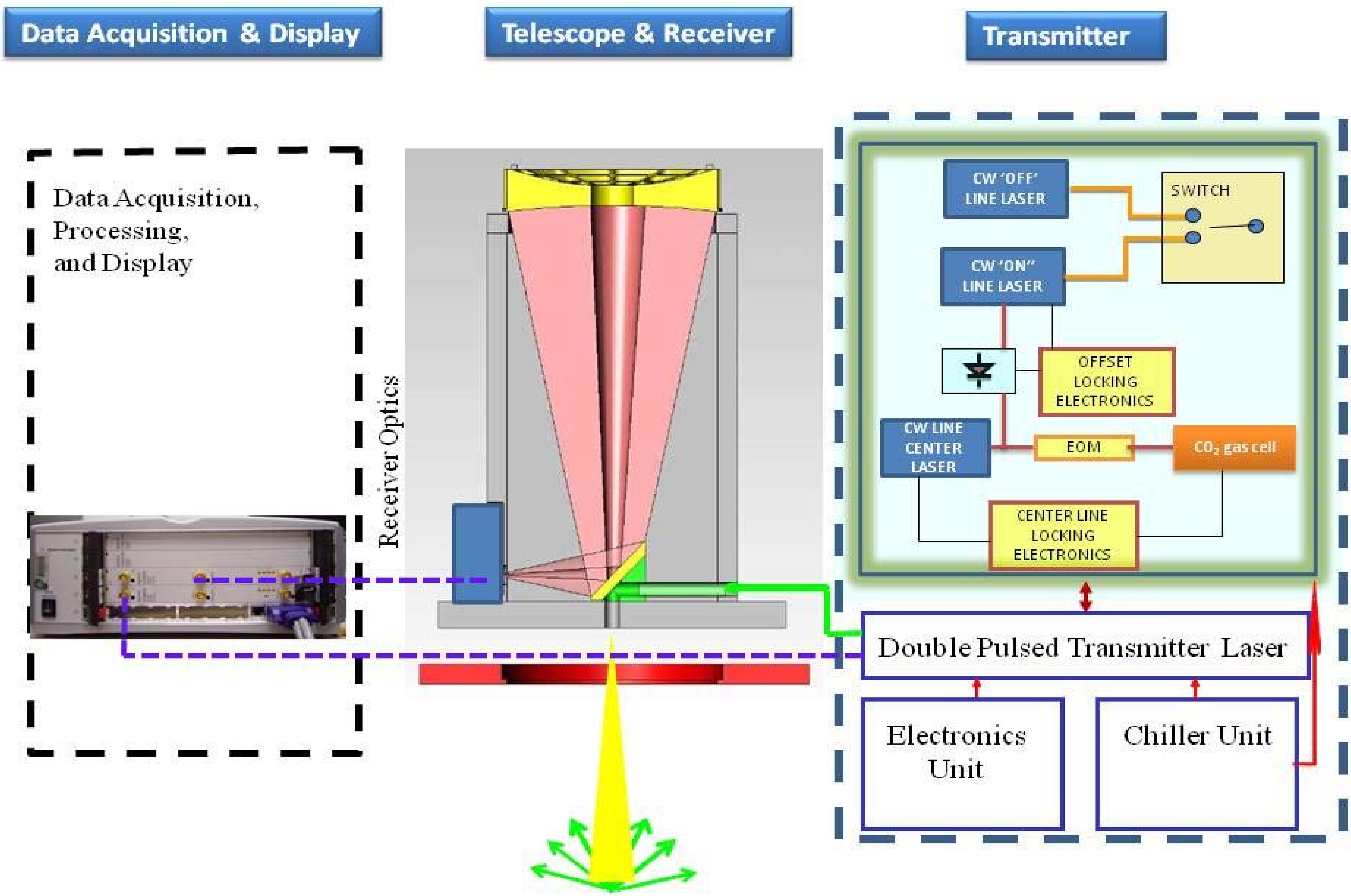
Transmitter

Wavelength (On / Off Line)	2051.023 / 2051.250 nm
Pulse Energy (On / Off Line)	100 / 45 mJ
Pulse Width (On / Off Line)	200 / 350 nsec
Pulse Repetition Rate	10 Hz (Double Pulse)
Laser Divergence Angle	160 µrad
CO2 Cell	8 m path length, 5 Torr
Lidar Configuration	Co-axial

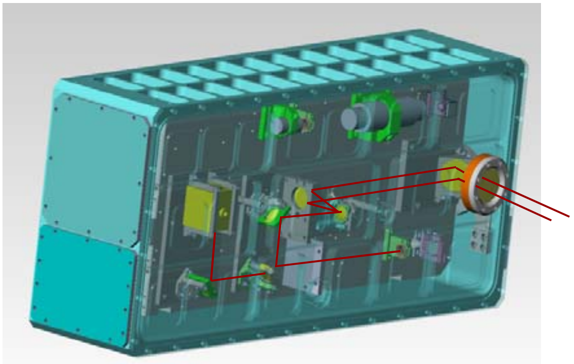
Receiver

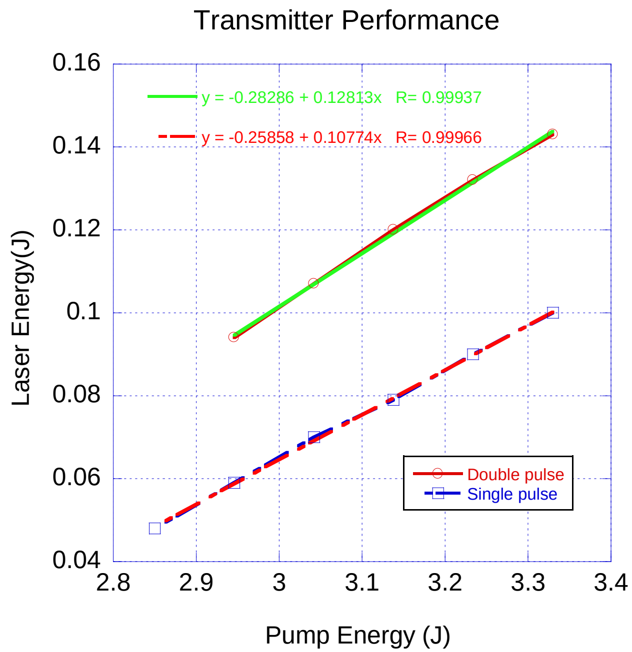
Newtonian Telescope Diameter	0.40 m f/2.3
Receiver Field-of-View	570 µrad
Detector	PIN: Hamamatsu G12183-203K
Detector Responsivity	1.15 A/W
TIA Gain	10^3 V/A – 10^6 V/A
Bandwidth	10 MHz
High / Low Gain Channel	90 / 10 %
Digitizer Rate	200MS / s

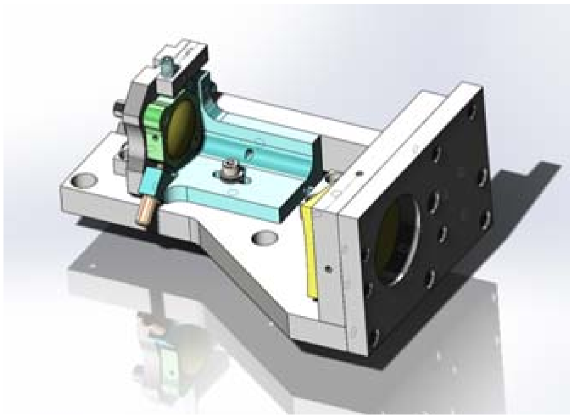
System Schematic



Laser Transmitter



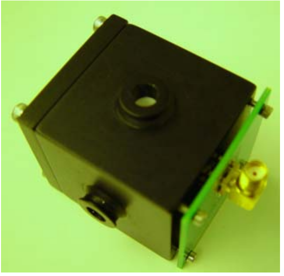


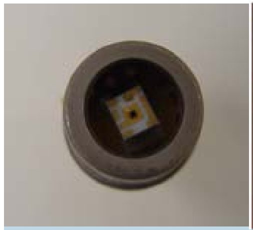


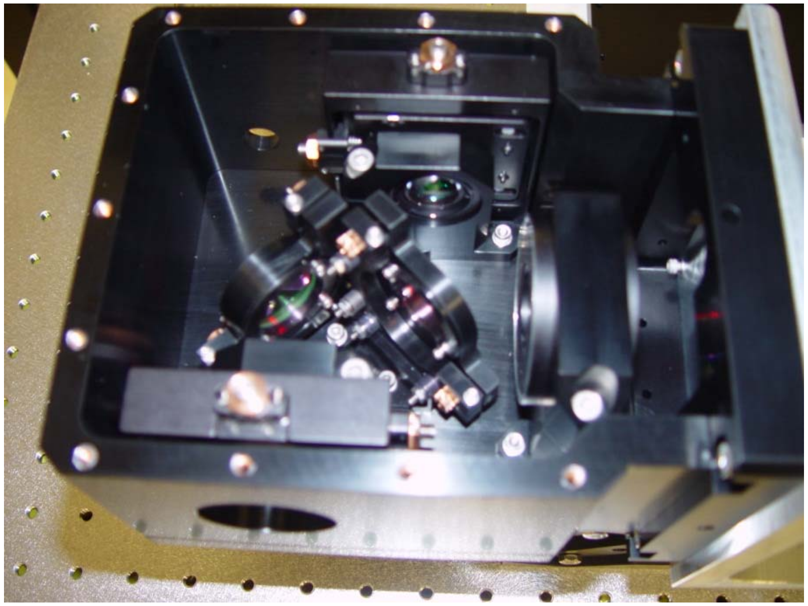
• Double Pulsed	~200µs between On/Off
• Injection Seeded	
• High Beam Quality	M^2 1.05
• Narrow Line Width	2.2 / 1.3 MHz
• Beam Expanded	0.16mrad
• Stable Operation	

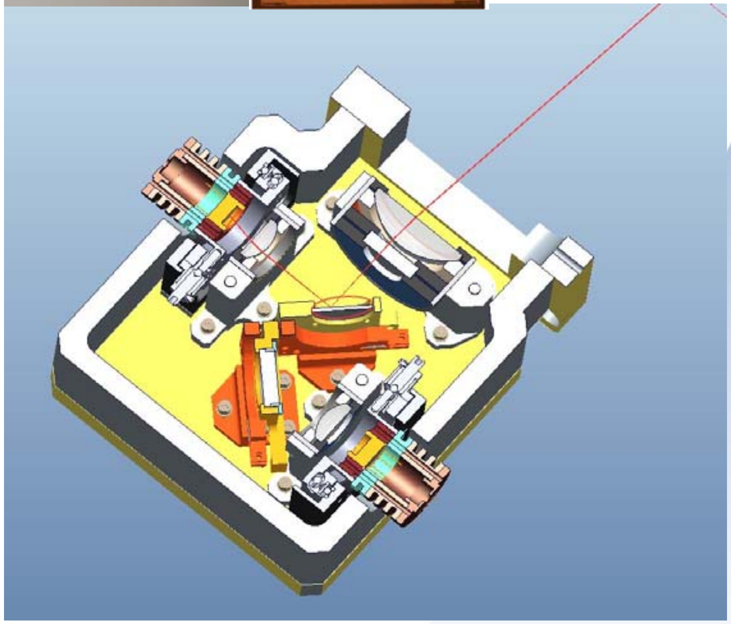
Aft Optics and Detector

- Two channel receiver design
- Pulse energy monitor
- Aft-optics
- Detector and preamplifier PIN InGaAs, FEMTO DHPCA-100
- Narrow band filter not applied

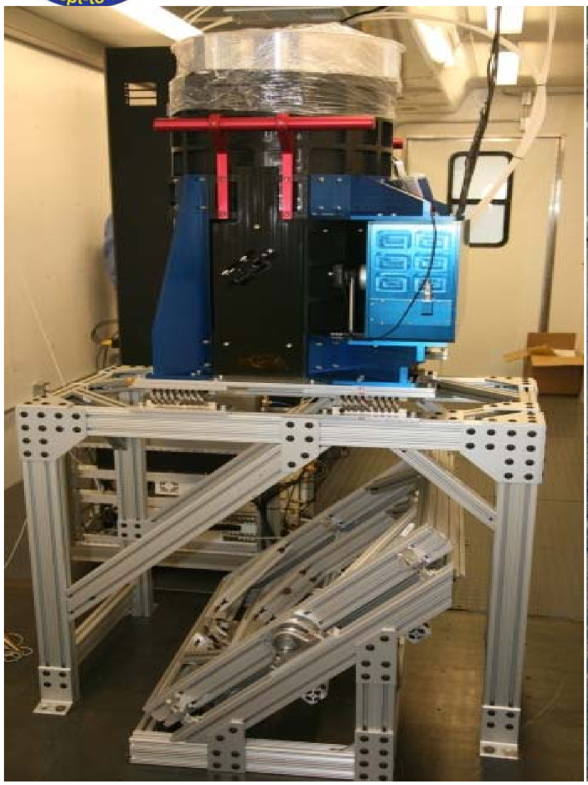








Ground Testing



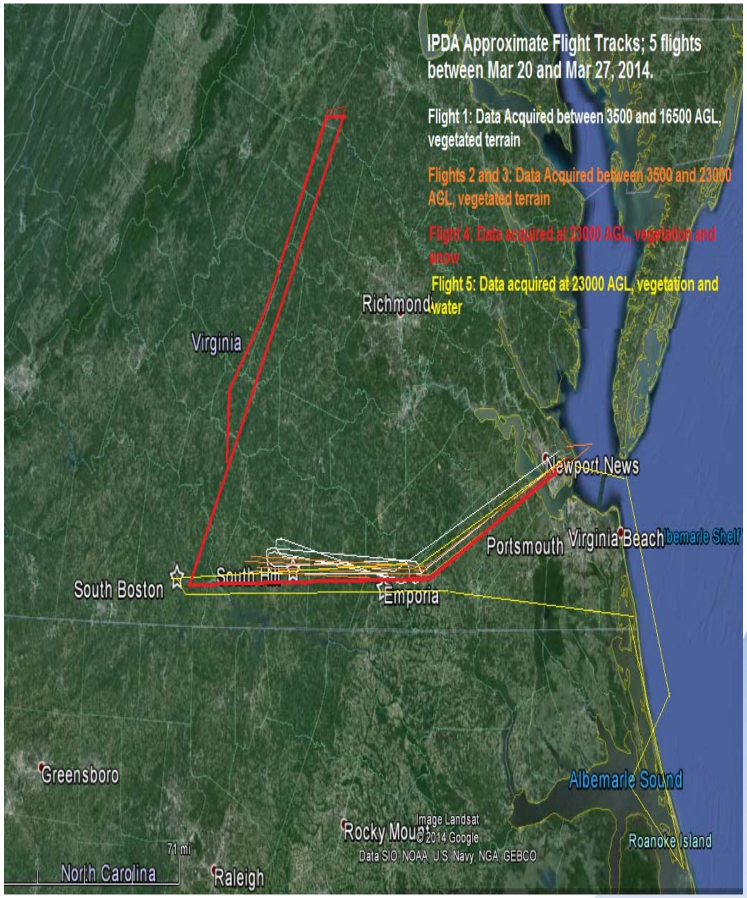
- Mobile lidar, configured and installed safety
- Calibrated target reflectivity at 2 micron wavelength
- Transmitter alignment to the telescope Field of View (FOV)
- Aligned the receiver Aft optics
- Characterize and Calibrate the narrow band width filters
- Establish pointing knowledge and stability
- Operated both during day and night, and several long duration data collected

2-micron Double Pulsed IPDA Lidar in Airplane

18

10 Flights in March & April 2014

Date	Purpose	Duration	Location
March 20	Instrument Check Flight	2.1 hr	VA
March 21	Engineering	2.7 hr	VA
March 24	Engineering	3.0 hr	VA
March 27	Early morning	3.0 hr	VA
March 27	Mid-afternoon	2.5 hr	VA
March 31	Inland-Sea	2.5 hr	VA, NC
April 02	Power Station	2.4 hr	NC
April 05	With NOAA	3.7 hr	NJ
April 06	Power Station	3.0 hr	NC
April 10	Late afternoon	2.3 hr	VA

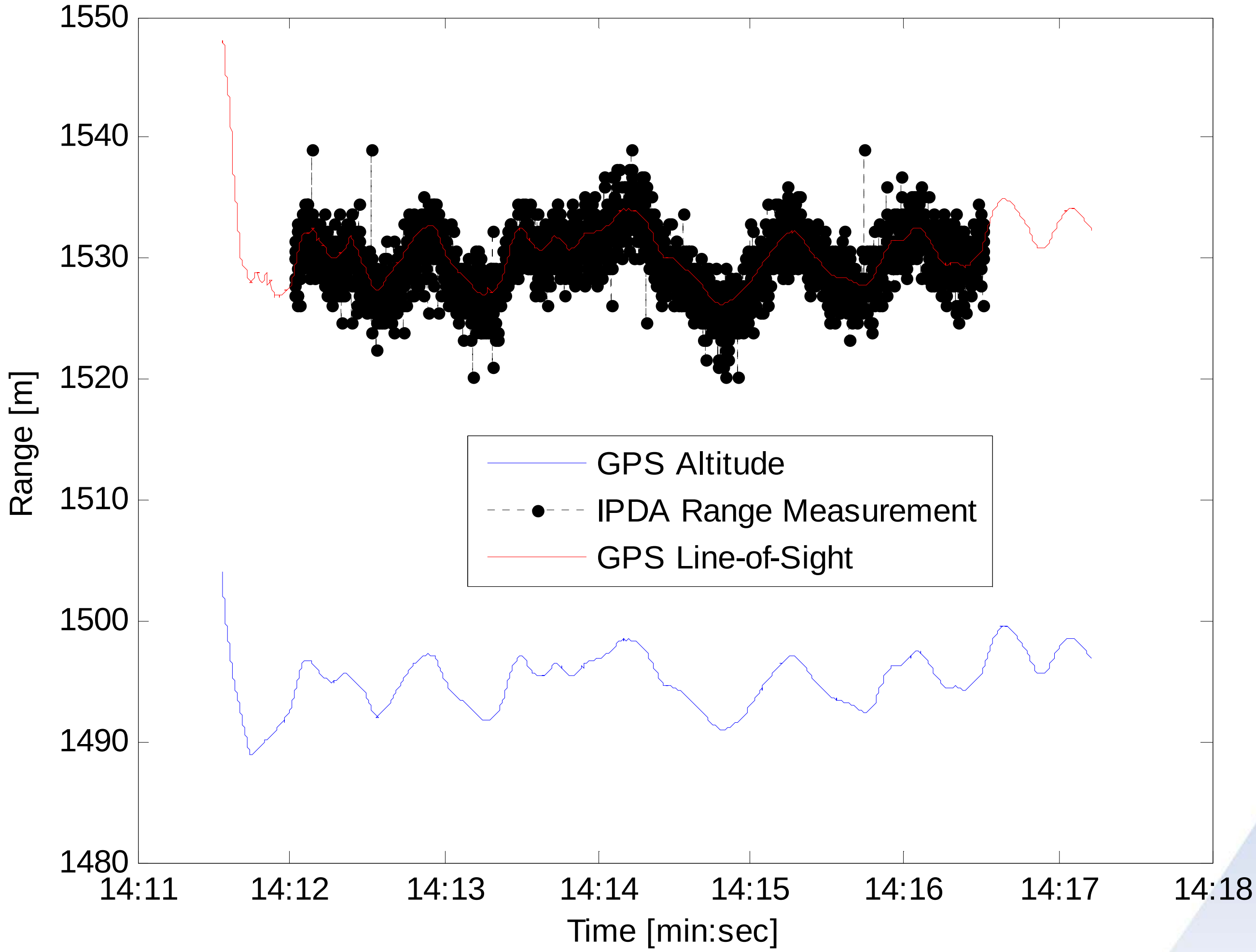


- Aircraft had temperature, pressure, humidity sensors, LiCor and GPS
- Some of the flights were supported by balloon launches

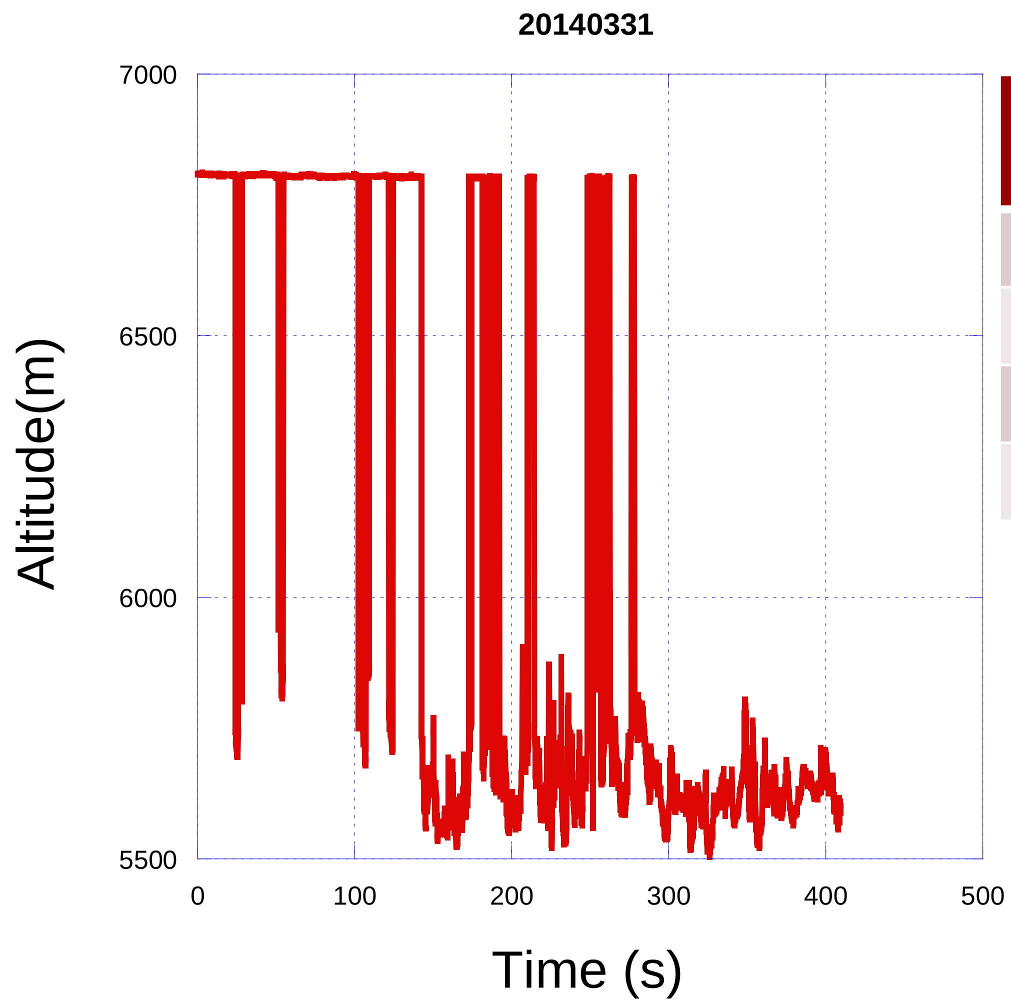
IPDA Lidar Capability

- Ranging
- Cloud Slicing
- Signals at various ground condition
- DAOD
- Power Station
- Flight data comparison with NOAA flights which collects a flask at multiple altitudes to obtain vertical profile

Ranging Capability

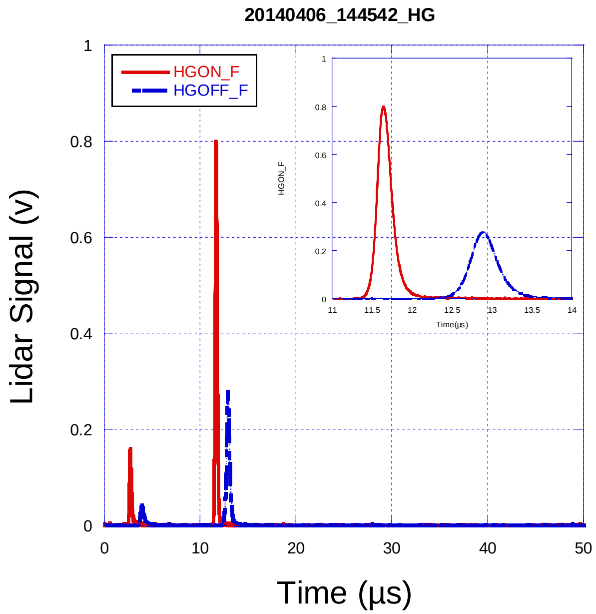


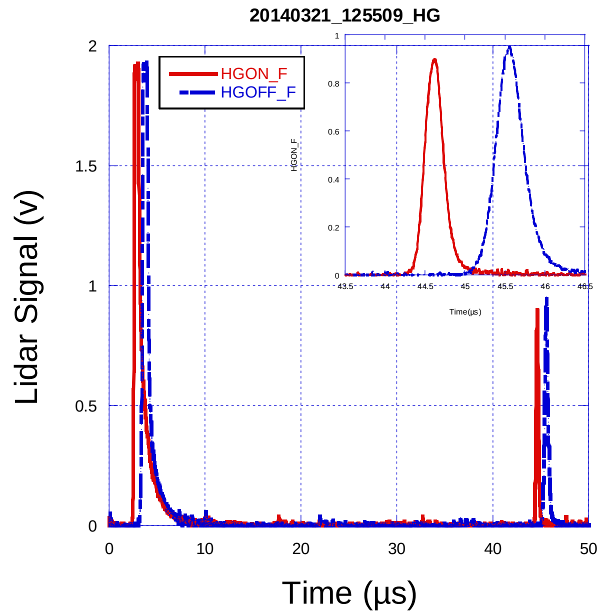
Cloud Slicing



	Alt. m	DAOD Lidar	DAOD Model	dDAOD
Ocean	6805	1.072	1.094	
Cloud	5631	0.757	0.782	
Lidar				0.315
Model				0.312

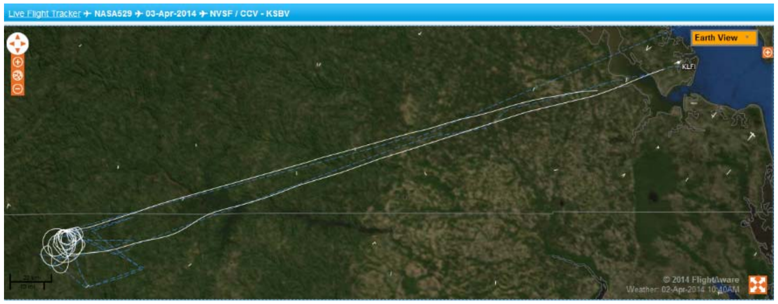
IPDA Airborne Lidar: Sample Return Signals

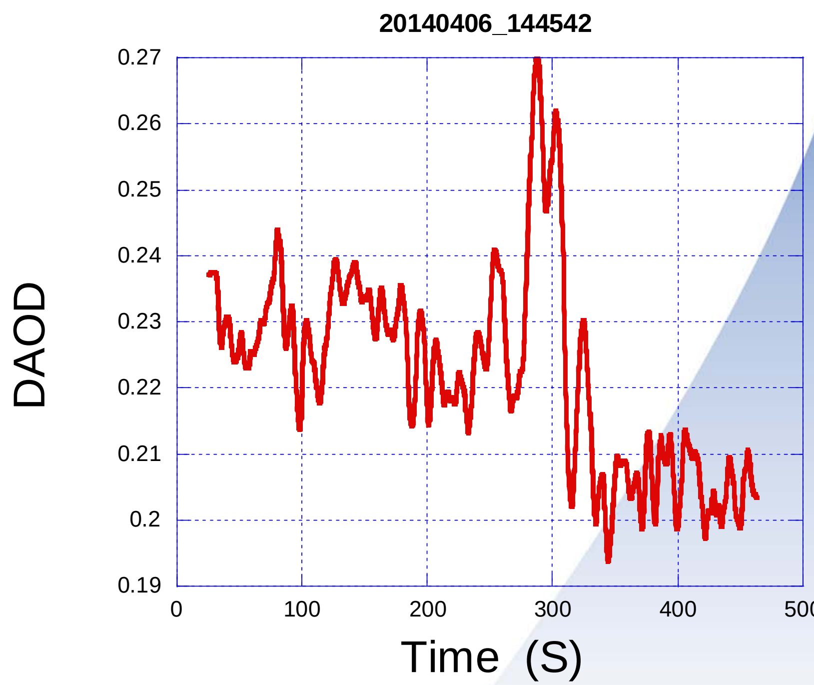




	Lidar Signal	SNR (peak)	SNR (power)	DAOD Model	DAOD w/mon.
Veg/Soil	1.89	398	485	1.0551	1.0550
Sea	0.552	111	139	1.0551	1.0883
Cloud	1.78	328	452	0.7805	0.757

Power Station Roxboro

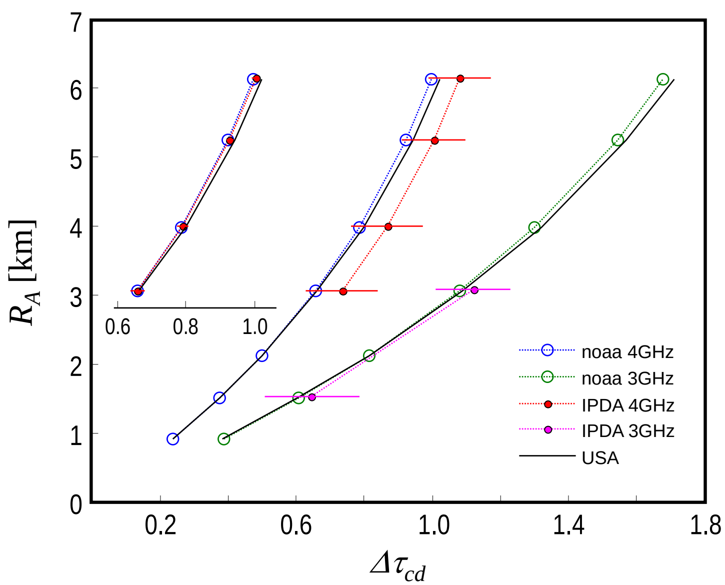




36° 28'52.79"N79° 04'08.97"W

IPDA Airborne Testing: Sample Return Signals

- NOAA air sampling and IPDA lidar optical depth comparison.
- Return signal samples from different altitudes up to 6km.
- IPDA range measurements compared to on-board GPS.



Comparison with the airborne air-sampling measurements

R_A	x_{cd}	$X_{cd,c}$	$X_{cd,m}$	$\delta X_{cd,m}$	ΔX_{cd}	$\varepsilon_{cd,m}$	$\beta_{cd,m}$
m	ppm	ppm	ppm	ppm	ppm	%	%
6125.6	400.75	404.08	405.22	4.15	1.14	1.02	0.28
5242.6	400.96	404.34	405.84	4.74	1.50	1.17	0.37
3976.7	401.61	404.89	406.60	8.69	1.71	2.14	0.42
3051.9	401.55	405.54	407.10	12.83	1.56	3.15	0.38

x_{cd},	airborne air-sampling measurements
X_{cd}	weighted average column dry-air volume-mixing ratio of CO_2 for 4 GHz on-line wavelength setting
$X_{cd,c}$	Obtained from modeling through NOAA data
$X_{cd,m}$	Obtained rom IPDA lidar DAOD measurements
$\delta X_{cd,m}$	IPDA X_{cd} measurement standard deviation
ΔX_{cd}	Offset, ($\Delta X_{cd} = X_{cd,m} - X_{cd,c}$)
$\varepsilon_{cd,m}$	Measurement error, ($\varepsilon_{cd,m} = \delta X_{cd,m}/X_{cd,m}$
$\beta_{cd,m}$	Measure bias ($\Delta X_{cd}/X_{cd,m}$)

Summary

- Developed a 2-μm double-pulsed laser transmitter and IPDA lidar system for CO_2 measurement
- Modeling and simulation of the 2-μm IPDA lidar instrument projected performance and science data retrieval algorithms
- Successful airborne IPDA lidar operation demonstrating robust integration and reliability
- Demonstrated airborne IPDA return signals obtained through different weighting functions and ground conditions, including soil, vegetation, ocean, sand and snow, beside cloud slicing capability all with high single-shot signal-to-noise ratio exceeding 100
- Bias and sensitivity verified through DAOD measurement
- Analysis of water vapor interference on CO_2 measurement indicated minimal error contribution due to precise selection, tuning and locking of the selected operational wavelengths.